Chapter 15
Model Studies

15-l. General

The development of satisfactory navigation conditions in the approaches to locks and dams and in critical reaches requires a knowledge of existing conditions with all navigable flows, changes produced by structures or modifications, and effects of changes on conditions affecting navigation. Adequate data are seldom, if ever, available to permit a reasonable analysis of the conditions existing in a particular reach and time will usually not permit a detailed survey of the reach (some of the flows that should be considered might not be experienced for several years). Because of the complex nature of flow in natural streams, analytical studies to determine probable conditions from a particular plan of improvement are generally extremely difficult and inconclusive, even if sufficient field data on existing conditions were available. An example of how model studies modified an original design is shown in Figures 15-1 and 15-2. The modifications were needed to assure safe approach conditions.

15-2. Use of Model Studies

Channel and overbank configurations and flow conditions are never identical in any two reaches of the same or different streams; designs that prove satisfactory at one site might not be adequate at another. For this reason model studies have been used extensively in the development of plans for locks and dams, bridge modifications, channel realignment, construction sequence, and for the reduction or elimination of channel maintenance. As a result of model studies, designs have been simplified in many cases, with considerable reduction in the cost of the project, and in others, the cost had to be increased because of the indicated need for better conditions and facilities.

Section I
Physical Model Studies *

15-3. Optimum Design

Small, financially insignificant changes in design can sometimes make the difference between good and bad navigation conditions. Correcting undesirable conditions before the structure is built can result in the elimination of costly maintenance and remedial measures. By using model studies, alternate plans and modifications can be tested within a relatively short time with all flow conditions that can be expected. Also, the design and operating engineers can observe conditions resulting with a particular arrangement and satisfy themselves as to the adequacy of the plan. In many cases, navigation interests are invited by the sponsors of the study to observe demonstrations of the plans developed, to operate the model towboats and tow, and to submit comments and recommendations. Utilization of this procedure results in the final design being based on the results of a complete investigation and the opinions and evaluations of the best qualified design engineers, engineers familiar with model investigations of these types of problems, and engineers responsible for operation of the facilities and the towing industry.

15-4. Cost of Model Studies

The cost of model studies varies with area under study, characteristics of the streams, nature of the problem, and number of plans and alternate plans to be tested before an acceptable solution is developed. The cost of model studies has usually been less than 0.10 percent of the cost of the project, a small price to pay for the assurance that the most practical and economical design has been developed. Both fixed-bed navigation models and movable-bed sedimentation models are recommended for lock and dam studies on alluvial streams. Only fixed-bed models are generally required for streams carrying little or no sediment.

* *Section II*
Numerical Model Studies

15-S. Numerical Models

a. Numerical modeling is a rapidly developing discipline that can be attributed to the general availability of fast, large-memory computers. A numerical model basically consists of a numerical algorithm developed from the differential equations governing the physical phenomena All numerical models require the study area to be discretized by a grid or mesh. Furthermore, testing the numerical results against a prototype data set (verification) is highly recommended.

b. Numerical models may be used to replace or supplement physical models. The following types of investigations can be studied with numerical models:

(1) Provide general circulation patterns for deep- or shallow-draft ship simulator studies.

(2) Determine shoaling and erosion characteristics.

(3) Address dredged material disposal issues and other water quality measures.

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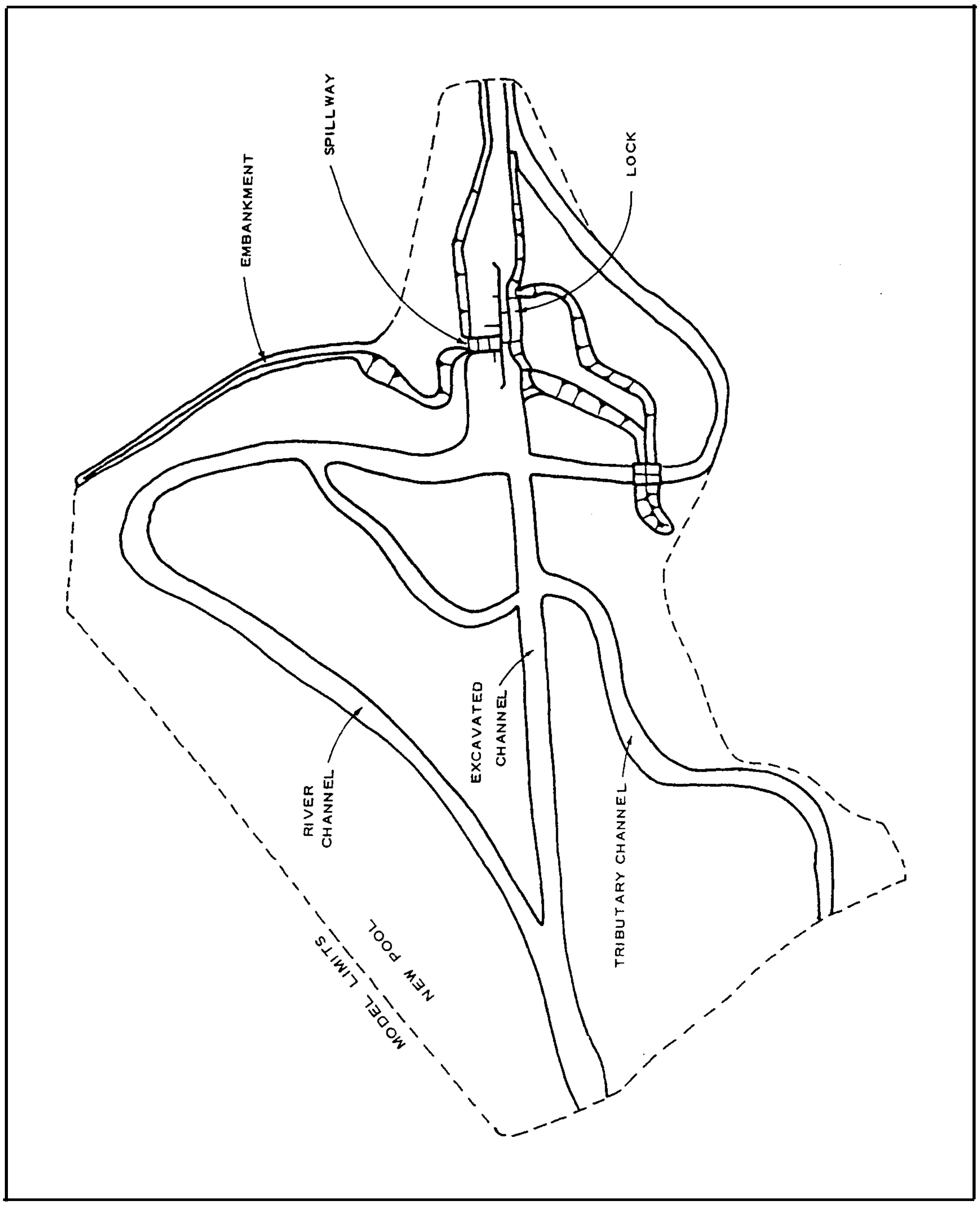

Figure 15-1. Original plan for lock and dam

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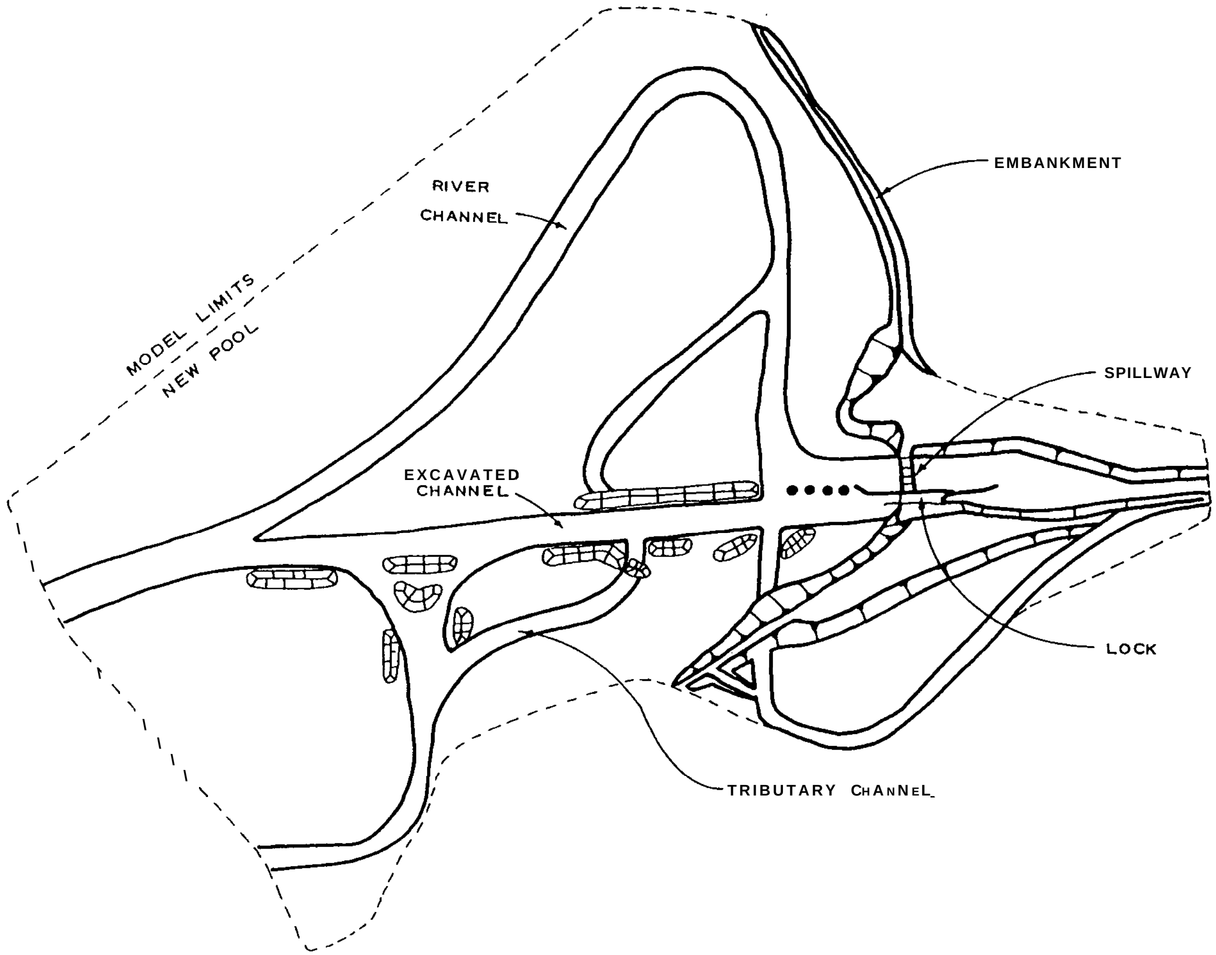

Figure 15-2. Improved plan based on model tests

* (4) Investigate salinity intrusion.

(5) Study wave penetration and harbor response.

(6) Evaluate training structure designs.

C. Numerous numerical models are available within the scientific community. These models differ in several ways: formulation, governing equations, and user friendliness, to name a few. Some numerical models have the ability to solve hydrodynamics and transport equations simultaneously while others are uncoupled.

d. The two basic numerical model formulations are finite difference and finite element. Finite difference is the easiest to conceptualize. A finite difference model approximates the calculus differential operators by differences over finite distances. This gives an approximation of the governing equations at discrete points. The finite element model approximates the mathematical form of the solution and inserts it into the exact form of the governing equations. After boundary conditions are imposed, a set of solvable simultaneous equations are created. The finite element solution is continuous over the area of interest.

e. The governing equations describe the physical processes that are being solved in the model. The dimensionality of the problem is dictated within these equations. These equations describe the physics of the problem For a hydrodynamic model these would include items such as friction, density, gravity, rotation of the earth, wind, rain, inflows, and outflows.

f. The term user friendly is an all-encompassing issue dealing with ease and efficiency of use. It addresses the process of creating a mesh, specifying the parameters within the computational domain, analyzing the solutions, generating presentation and report quality graphics, on-line documentation, and consultation support.

g. Several models are available within the U.S. Army Corps of Engineers **(USACE)** that have met the test of time. One such model is the TARS-MD numerical modeling system The multidimensional aspects of TABS-MD have expanded the capabilities of the system such that it has had hundreds of applications within the USACE. TABS-MD has been utilized by a multitude of private consulting firms and universities as well. It has a good reputation and a state-of-the-art graphical user interface that makes it one of the most user-friendly and efficient ways to conduct a numerical model study. Numerous technical reports and papers have been published on TABS-MD applications, the most recent of which are listed in Appendix A.

15-6. TABS-MD Numerical Modeling System

a. The TABS-MD is a collection of several generalized finite element models and pre- and post-processing utility programs integrated into a multidimensional numerical modeling system TARS-MD is suitable for use in solving hydraulics behavior, sedimentation, and transport problems of rivers, reservoirs, wetlands, estuaries and bays. Examples of past use include predicting flow patterns and erosion in a river reach constricted by a cofferdam, evaluating sedimentation rates in a deepened navigation channel (both riverine and estuarine), determining the impact of flood control structures on salinity intrusion, developing recommendations for a safe and cost-effective navigation channel design, and defining flow and sedimentation impacts to wetlands.

b. The system is designed for use by engineers and scientists who are knowledgeable of the physical processes that control behavior of waterways, but who may not be computer experts. TABS-MD offers a complete range of model study functions, including map digitization, mesh generation, modeling, and graphical display of numerical model results.

c. TABS-MD is currently operational on a wide variety of computer platforms, ranging from the CRAY super computer to the personal computer (PC). The numerical models and most of the utility programs are written in FORTRAN-77 and will soon be updated to FORTRAN-90. Plans am underway to modify the models to take advantage of parallel processor environments.

d. The system is maintained by the U.S. Army Engineer Waterways Experiment Station (WES), and includes two hydrodynamic models: RMA2-WES and RMA10-WES. In this context, the term hydrodynamic modeling is a general term intended to denote a body of water with a free surface such as a river. The first fundamental decision, prior to conducting a numerical model study, is to classify the study area in order to choose the appropriate numerical model. RMA2-WES is an appropriate choice for a far-field problem whose study area may be modeled with a two-dimensional (2-D) depth-averaged approximation. Otherwise, the modeling effort must employ RMA10-WES to incorporate the three-dimensional (3-D) aspects. TABS-MD permits an efficient numerical approach by incorporating multiple dimension concepts within a given mesh domain. For instance, a RMA2-WES application may use economical one-dimensional (1-D) calculations in some areas and 2-D ones within the primary area of interest. A RMA10-WES application may *

* use any combination of l-, 2-, and 3-D calculations with or without the transport options. Needless to say, the modeling effort can reach a high degree of complexity and computational burden with 3-D computations.

Two sediment transport options are available with the TABS-MD system SED2D is a 2-D finite element model that solves the convectiondiffusion equation with bed source-sink terms. These terms are structured for either sand or cohesive sediments. Cohesive deposited material forms layers, and bookkeeping allows layers of separate material types, deposit thickness, and age. SED2D uses the hydrodynamic solution generated by the RMA2-WES model. RMA2-WES and SED2D are uncoupled, therefore, a new geometry must be cycled back to RMA2-WES when the bed deposition and erosion patterns begin to significantly affect hydrodynamics. Work is ongoing to upgrade SED2D to accommodate all features of RMA2-WES, such as 1-D and marsh/wetland calculations. The other sediment transport option is to couple the sediment transport with the hydrodynamic calculation by using RMA10-WES. RMA10-WES includes a single-class fine-sediment transport with an associated layered bed with distinct densities and erodibilities for each layer. Changes in bed elevation are made during computations and are accounted for in the continuity equation.

f. There are two water quality transport options within TABS-MD as well. RMA4-WES is a 1-D and 2-D finite element model with a form of the convective diffusion equation with general source-sink terms. The model may transport and route up to six constituent substances, with or without decay. The model accommodates a mixing zone outside the model boundaries for estimation of re-entraimnent. RMA4-WES uses the hydrodynamic solution generated by the RMA2-WES model. RMA10-WES has the option to couple temperature, salinity, and/or sediment transport with the hydrodynamic calculations.

A recent research effort was conducted at WES to provide guidelines and help field offices conduct hydrodynamic numerical models to address both deep-draft and shallow-draft issues. The work emphasized RMA2-WES hydrodynamic applications since all navigation studies involve that aspect and most of the field offices have access to personal computers or workstations capable of running 2-D simulations. Furthermore, the WES ship simulator typically uses the RMA2-WES solution as input to define the currents for the simulator (Figure 15-3).

15-7. Example Navigation Applications using RMA2-WES Solutions

a. ***Charleston, SC. Estuary.*** The study was undertaken to evaluate and optimize proposed improvements including deepening the navigation channel from 40 to 45 feet, realigning and/or widening several fairways along a 5-mile stretch of the estuary, and locating a proposed seven-berth container terminal. The RMA2-WES simulation was conducted to provide currents to the WES ship simulator for several time-steps on both the ebb and flood portions of a spring tidal cycle. Figure 15-3 shows the WES ship simulator response track plot corresponding with one set of velocity vectors computed by RMA2-WES for the Drum Island reach of the study area. The study was an iterative process between the hydrodynamic model, the ship simulator model, and the SED2D sediment transport model, as indicated by the flowchart in Figure 15-4.

b. *Redeye Crossing near Baton Rouge, LA, along the Lower Mississippi River.* The study was undertaken to evaluate the effect of river training structures on vessels (both ships and tows) transiting the Redeye Crossing Reach. Studies included a TABS-MD RMA2-WES hydrodynamic model, the ship/tow simulator model, and a SED2D sediment transport model. Figure 15-5a and b show the WES tow simulator response track plot corresponding to one set of velocity vectors computed by RMA2-WES using the secondary flow corrector. Figure 15-5c shows the computational mesh used by the TABS-MD models. The study was an iterative process between the RMA2-WES hydrodynamic model, the ship simulator model, and the SED2D sediment transport model, as indicated by the flowchart in Figure 15-4.

15-8. RMA2-WES Hydrodynamic Model

RMA2-WES is a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with Manning's equation, and eddy viscosity coefficients are used to define the turbulent exchanges. A velocity form of the basic equation is used with side boundaries treated as either slip or static. The model has a marsh porosity option as well as the ability to automatically perform wetting and drying. Boundary conditions may be water-surface elevations, velocities, discharges, or tidal radiation. Both steady and unsteady free-surface calculations for subcritical flow problems can be analyzed.

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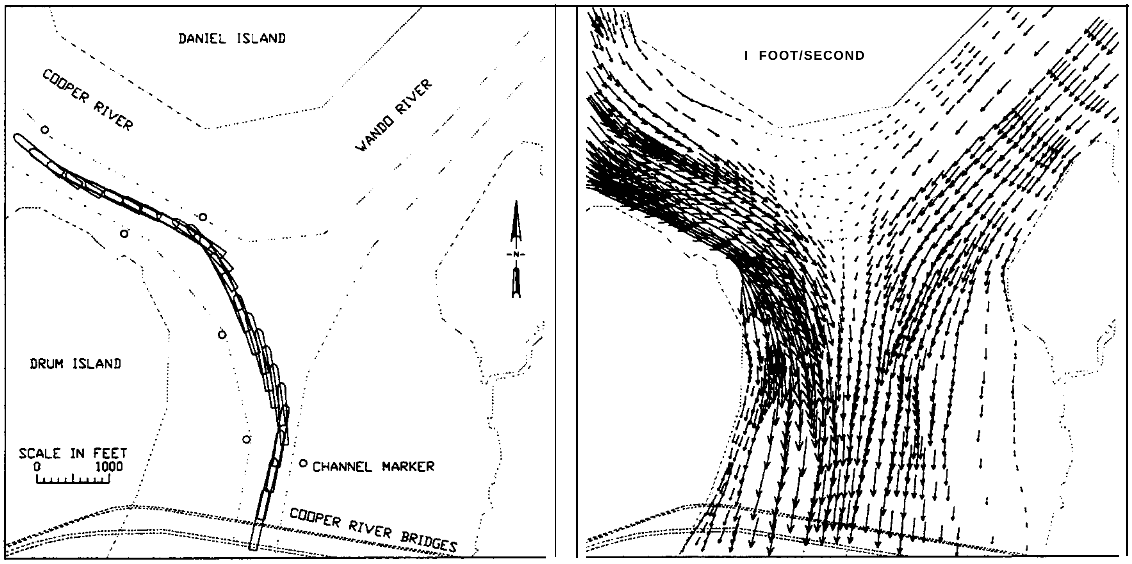

a. WES ship simulator track plot

b. RMA2-WES hydrodynamic solution

Figure 15-3. The Cooper River, Charleston, SC, channel realignment study

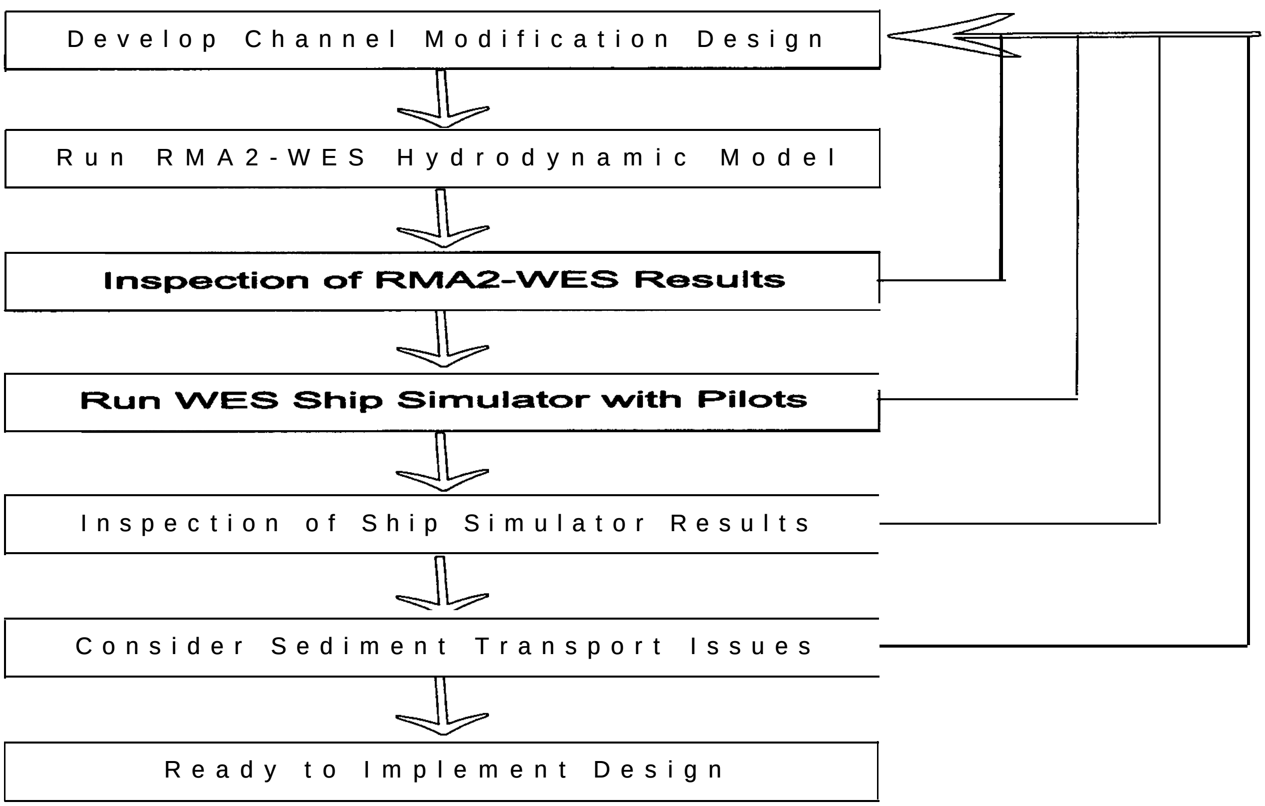

Figure 15-4. Typical events and feedback loops involved in WES ship simulator study

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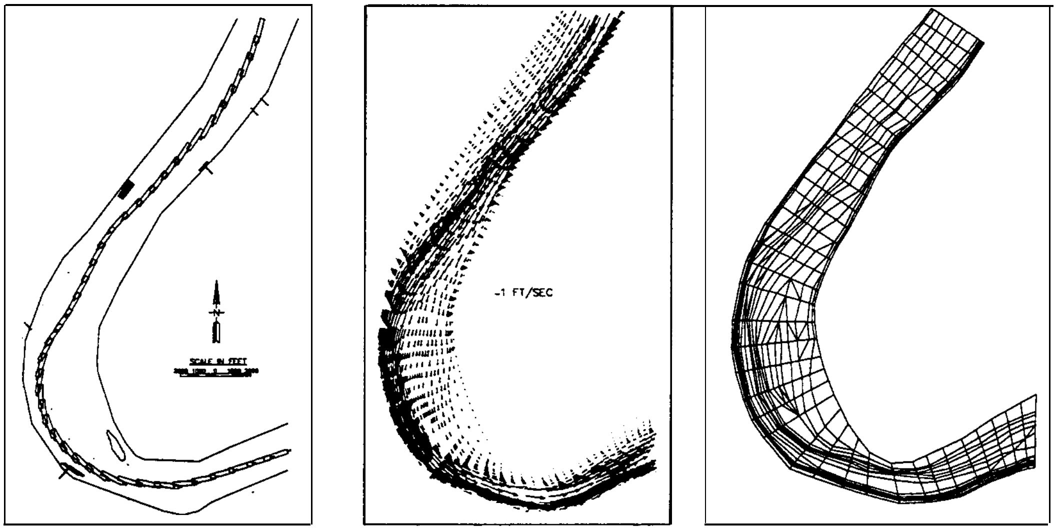

a. WES tow simulator track plots **b. RMA2-WES hydrodynamic solution** **c. Numerical model computational mesh**

Figure 15-5. Redeye Crossing of the Lower Mississippi River

a. RM42- WES governing equations.

(1) The generalized computer program RMA2-WES solves the depth-integrated equations of fluid mass and momentum conservation in two horizontal directions. The forms of the solved equations are

$$h\frac{\partial u}{\partial t} + hu\frac{\partial u}{\partial x} + hv\frac{\partial u}{\partial y} - \frac{h}{\rho}\left(E_{xx}\frac{\partial^2 u}{\partial x^2} + E_{xy}\frac{\partial^2 u}{\partial y^2}\right) + gh\left(\frac{\partial a}{\partial x} + \frac{\partial h}{\partial x}\right) + \frac{gun^2}{(1.486h^{1/6})^2}\left(u^2 + v^2\right)^{1/2} - \zeta V_a^2 \cos\psi - 2h\omega v \sin\phi = 0 \tag{15-1}$$

$$h\frac{\partial v}{\partial t} + hu\frac{\partial v}{\partial x} + hv\frac{\partial v}{\partial y} - \frac{h}{\rho}\left(E_{yx}\frac{\partial^2 v}{\partial x^2} + E_{yy}\frac{\partial^2 v}{\partial y^2}\right) + gh\left(\frac{\partial a}{\partial y} + \frac{\partial h}{\partial y}\right) + \frac{gvn^2}{(1.486h^{1/6})^2}\left(u^2 + v^2\right)^{1/2} - \zeta V_a^2 \sin\psi + 2\omega hu \sin\phi \tag{15-2}$$

$$\frac{\partial h}{\partial t} + h\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} = 0 \tag{15-3}$$

*

* where

h = depth

u,v = velocities in the Cartesian directions

x,y,t = Cartesian coordinates and time

ρ = density of fluid

E = eddy viscosity coefficient, for xx = normal direction on x-axis surface, for yy = normal direction on y-axis surface, for xy and yx = shear direction on each surface

g = acceleration due to gravity

a = elevation of bottom

n = Manning's roughness n-value

1.486 = conversion from SI (metric) to non-SI units

ζ = empirical wind shear coefficient

V_a = wind speed

ψ = wind direction

ω = rate of earth's angular rotation

ϕ = local latitude, Coriolis

(2) Equations 15-1 through 15-3 are solved by the finite element method using the Galerkin method of weighted residuals. The elements may be 1-D lines, or 2-D quadrilaterals or triangles, and may have curved (parabolic) sides. The shape functions are quadratic for velocity and linear for depth. Integration in space is performed by Gaussian integration. Derivatives in time are replaced by a nonlinear finite difference approximation. Variables are assumed to vary over each time interval in the form

$$f(t) = f(0) + at + bt^c \qquad t_0 \le t \le t_0 + \Delta t \qquad (15\text{-}4)$$

which is differentiated with respect to time, and cast in finite difference form. Letters a, b, and c are constants. It has been found by experiment that the best value for c is 1.5 (Norton and King 1977).

(3) The solution is fully implicit and the set of simultaneous equations is solved by Newton-Raphson nonlinear iteration. The computer code executes the solution by means of a front-type solver, which assembles a portion of the matrix aud solves it before assembling the next portion of the matrix.

(4) RMA2-WES is based on the earlier versions (Norton and King 1977) but differs in several ways. It is formulated in terms of velocity (v) instead of unit discharge (vh), which improves **some aspects** of the code's behavior. Other differences from the earlier versions include the following:

(a) Employs new numerical solution algorithms.

(b) Permits wetting and drying of areas within the mesh.

(c) Permits wetlands to be simulated as either totally wet/dry or as gradually changing wet/dry states.

(d) Permits specification of turbulent coefficients in directions other than along the x- and z-axes.

(e) Accommodates the specifications of hydraulic control structures in the network.

(f) Permits the use of automatic assignment of friction and turbulent coefficients.

(g) Permits input in either non-SI or SI units.

(5) Additionally, the following have been incorporated into the RMA2-WES model as a result of deep- and shallow-draft research and applications.

(a) Incorporated a secondary flow ('bendway") corrector.

(b) Improved the RMA2-WES documentation and provided resolution guidelines.

(c) Provided an on-line point-and-click documentation capability on the PC.

(d) Incorporated a documentation icon within the graphical user interface on the PC. *

b. The principle of bendway correction.

(1) The secondary flow (or "bendway") corrector was added to the RMA2-WES model. The modified program, designated as version 4.35, solves a transport equation for streamwise vorticity and converts it to accelerations due to secondary currents. These additional accelerations result in improved predictions of the traditional depth-averaged velocity calculations. Their effect is to reduce velocities on the inside of river bends and increase them on the outside of bends. The modeler may activate or deactivate the secondary flow corrector as required for its application. This enhancement permits RMA2-WES to be successfully used for some study areas that otherwise would have required the 3-D model.

(2) The theoretical basis of the bendway correction was developed for the depth-averaged finite difference numerical model, STREMB (Bernard and Schneider 1992).

(3) The bendway correction is accomplished by first solving an additional equation for the transport of streamwise vorticity. Vorticity is a measure of rotation of flow. Streamwise vorticity at a point is equal to the velocity of the fluid about the axis in the streamwise direction of flow. Streamwise vorticity is in the vertical plane perpendicular to the direction of flow and is related to the radial accelerations that cause the helical flow pattern.

(4) The transport equation for streamwise vorticity is

$$\frac{\partial \Omega}{\partial t} + \frac{\partial \Omega}{\partial x} + \frac{\partial \Omega}{\partial y} = \frac{A_S \sqrt{C_f}\,|u|^2}{Rh\left(1 + 9h^2 / R^2\right)} - D_S \sqrt{C_f}\,\Omega \frac{|u|}{h} + \frac{1}{h}\nabla\,(vh\nabla\Omega) \qquad (15\text{-}5)$$

where

Ω = streamwise vorticity

$A_S = 5.0$

C = friction coefficient

$|u|$ = magnitude of the velocity vector

R = local radius of curvature

$D_S = 0.5$

Units of vorticity are sec^{-1}.

(5) The additional shear stress caused by the secondary, helical flow is calculated from streamwise vorticity at each node. The components of this shear stress are added to the other terms (friction, slope, Coriolis) in the governing equations.

15-9. RMA2-WES Documentation

With the technological advancements of the computer industry and the evolution of computational algorithms, it was evident that published documentation could be quickly outdated. To address the evolution of the "art" of numerical modeling, a living approach to documentation was selected. The RMA2-WES ***"DOC-TO-HELP"*** hypertext documentation is regularly updated and available for download from the World Wide Web (WWW). After downloading it to your PC, you may view the on-line documentation on any PC running windows. The WWW address for the documentation:

http://hlnet.wes.army.mil/software/tabs/tabs.htm

15-10. Graphical User interface

All USACE employees performing surface water analyses for the USACE may obtain a copy of the Graphical User Interface developed by Brigham Young University (BYU). Two generations of graphical interfaces are compatible with TABS-MD: FastTABS (1989-1994) and SMS (1995-present). To obtain a copy of the SMS interface, download the proper executable for your computer site and complete the request form available from the WWW at this address:

http://hlnet.wes.army.mil/software/interfaces/sms/smsreg.htm

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